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Analyzing the agricultural transition in Mato Grosso, Brazil, using satellite-derived indices

Abstract

The Amazonian state of Mato Grosso is the main production area for soybeans in Brazil and contains 31.3% of the national production as of 2009. The rapid evolution of the agricultural systems in this area shows that the region is experiencing a rapid agricultural transition. In this paper, we broke down this transition process into three steps: crop expansion, agricultural intensification and ecological intensification. We used remote sensing products to develop and compute satellite-derived indices describing the main agricultural dynamics during the cropping years from 2000-2001 to 2006-2007. Our results indicated that Mato Grosso is continuing to expand its agricultural sector, with a 43% increase in the net cropped area during the study period. Although this expansion mainly occurred in the cerrado ecoregion until the early 2000s, the forest ecoregion is experiencing expansion at this time. We observed that 65% of the crop expansion in Mato Grosso from 2000 to 2006 occurred in this ecoregion. However, we did not identify this crop expansion as the major driver of deforestation in Mato Grosso because only 12.6% of the cleared areas were directly converted into croplands. Agricultural intensification also evolved rapidly, as the proportion of the net cropped area cultivated with double cropping systems harvesting two successive commercial crops (i.e., soybean and corn or soybean and cotton) increased from 6% to 30% during the study period. Finally, we found that ecological intensification occurred because the region's farmers planted a non-commercial crop (i.e., millet or sorghum) after the soybean harvest to prevent soil erosion, improve soil quality, break pest cycles, maintain soil moisture and set the conditions for high-quality no-tillage operations. In 2006-2007, 62% of the net cropped area was permanently covered by crops during the entire rainy season. This practice allowed the

farmers to diversify their production, as shown by the positive evolution of the Area Diversity Index. Future scholars can use the method proposed in this paper to improve their understanding of the forces driving the agricultural dynamics in Mato Grosso.

Keywords: Amazon, agricultural intensification, crop expansion, cropping systems, deforestation, remote sensing.

1. Introduction

Agricultural ecosystems provide and rely on provisions (i.e., food, fuel, timber), support (i.e., soil fertility), cultural services (i.e., recreation, spiritual services) and regulation (i.e., flood control, pollination, biodiversity) (Zhang et al., 2007). Historically, farmers have focused on improving these ecosystems' provisioning services by increasing the food production via agricultural expansion to address the needs of a growing population (Borlaug, 2000a). Since the 1950s, the drastic growth of the world population has highlighted the limits of the agricultural expansion model's capacity to provide sufficient food. More intensive agricultural practices were adopted during the Green Revolution (Borlaug, 2000b; Matson et al., 1997; Tilman, 1999). However, given that scholars have also criticized the Green Revolution because of its impact on the ecosystems' support, cultural and regulatory services, the agricultural intensification model seems to have reached its limits (Conway and Toenniessen, 1999; Tilman et al., 2002; Godfray et al., 2010). For these reasons, nowadays farmers must adopt new practices to improve or maintain the ecosystems' provisioning services while maintaining and/or retrieving the systems' support, cultural and regulatory services. Researchers have named this new model ecological intensification (Cassman, 1999), conservation agriculture (FAO, 2010) or sustainable intensification (Godfray et al., 2010).

1 Thus, the evolution from an agricultural expansion model toward an ecological intensification
2 model can be described as a transition toward agricultural sustainability (Ruttan, 1999). All
3 agricultural regions are expected to experience this transition. In temperate regions, the Green
4 Revolution has evolved successfully such that the cultivated areas are now decreasing (Lepers
5 et al., 2005). Currently, the new challenge is to adopt an ecological intensification model.
6 Because the agricultural transition started much later in tropical regions such as Brazil, the
7 agricultural expansion model remains the main method for increasing the regions' agricultural
8 production (Geist and Lambin, 2001). However, new agricultural practices are being rapidly
9 disseminated as societies are becoming increasingly concerned with environmental issues.
10 Brazil's federal government has encouraged the development of agriculture in the Brazilian
11 Amazon since the 1970s. Migrants were supported to clear the forests and Brazilian savannah
12 (cerrado) to expand the cropped areas and to rear cattle (Muchagata and Brown, 2003; Jepson,
13 2006; Dubreuil et al., 2008). At the same time, scientific and technological development
14 enabled farmers to cultivate major commodity crops, such as soybean and corn, in this
15 tropical environment by correcting the high acidity and low fertility of the region's
16 soil (Spehar, 1995; Warnken, 1999; Costa et al., 2002). Mato Grosso has been most affected by
17 this development because of its location on Brazil's southern frontier and because of
18 governmental incentives. Migrants coming from the Southern states of Brazil have developed
19 a mechanized agricultural system mainly based on exporting soybean crops since the 1970s
20 (Dubreuil, 2002; Jepson, 2006; Dubreuil et al., 2008). Agricultural expansion and new
21 intensive systems led Mato Grosso to become a national and international agricultural center
22 of crop production, with approximately 58315 km² of land planted in soybeans (i.e., 26.8% of
23 the national cropland planted in soybeans) in 2009 (IBGE, 2010). However, the agricultural
24 model adopted in Mato Grosso caused numerous environmental problems, such as a loss of
25 biodiversity due to deforestation, hydro sedimentological changes in the watersheds, erosion

1 and water pollution. As a result, new environmental governance systems involving state
2 actors, civil society organizations and private actors are proposing new policies to incentivize
3 Mato Grosso's farmers to actively address these issues (Brannstrom, 2009). According to
4 Nepstad and Stickler (2008), these policies may focus on implementing an integrated
5 certification system for commodity sanitation, rigorous environmental standards, and sound
6 labor practices, which should become the norm for participation in commodity markets.
7 Examples of agro-industrial reforms include the Mato Grosso licensing and control system
8 created by the state government (Fearnside, 2003) and the Soy Moratorium established in
9 2006 (Brannstrom, 2009; Rudorff et al., 2011).

10 To monitor the evolution of Mato Grosso's agricultural systems, we must obtain accurate
11 agricultural statistics. The official statistics provided by IBGE (i.e., Brazilian Institute of
12 Geography and Statistics) are based on declarative data aggregated at the county level and do
13 not account for cropping systems. In this study, we argue that the use of remote sensing
14 techniques can help solve these issues and improve the agricultural statistics. Previous
15 scholars have recognized these techniques as efficient tools for quantifying and understanding
16 land use changes (i.e., either conversions or modifications) (Lambinet al., 2001; Coppin et al.,
17 2004). For instance, many researchers have used satellite images to observe land use
18 conversions, such as deforestation (Achard et al., 2001; Hansen et al., 2010) and crop
19 expansion (Erickson, 1984; Gallego, 1999; Lepers et al., 2005). Scholars have also
20 successfully mapped the crops grown in Mato Grosso based on MODIS data (Jasinskiet al.,
21 2005; Morton et al., 2006; Brown et al., 2007; Galford *et al.*, 2008; Arvor et al., 2011).
22 Morton et al. (2006) estimated that approximately 16% of the total deforestation in Mato
23 Grosso's Amazonian forest from 2001 to 2004 was directly due to crop expansion. Finally,
24 Brown et al. (2007) and Galford et al. (2008) conducted research based on their classifications
25 of the vegetation index time-series that they extracted from MODIS data to observe land use

modifications, such as agricultural intensification caused by the adoption of double cropping systems. Their work, which was based on their analysis of two localities (i.e., one in Mato Grosso and one in the state of Rondonia located on the western border of Mato Grosso), illustrated the progress of agricultural intensification in Mato Grosso.

The goal of this paper is to derive a complementary methodology designed to clarify at a regional level the land use changes observed in Mato Grosso in terms of the agricultural transition process (see also DeFries et al. 2004 for a review of the stages in land use transition associated with the agricultural transition process). Therefore, our main objectives are threefold: (i) to characterize the agricultural expansion process by paying special attention to its impact on deforestation in the cerrado and forest ecoregions, (ii) to typify the agricultural intensification process by analyzing the spatio-temporal evolution of the region's double cropping systems, and (iii) to evaluate the ongoing progress of the region's ecological intensification by studying Mato Grosso's permanently covered areas and crop diversification. To satisfy these objectives, we calculated satellite-derived indices for each stage of the transition process from 2000 to 2006.

2. Study area

2.1. Environmental issues and recent history

The state of Mato Grosso encompasses an area of 906000 km² (Fig. 1) and is located in the southern part of the Legal Brazilian Amazon. The climate is characterized by a rainy season that lasts from September to April. According to a South–North gradient, the average annual rainfall ranges from 1200 to 2000 mm. The natural vegetation reflects a high diversity of landscapes represented by three main ecoregions: the Amazonian forest, the cerrado and the

1 Pantanal. Each ecoregion has been recognized for its importance to global biodiversity as
2 hotspots of diversity (cerrado and Pantanal; Myers et al., 2000) or wilderness areas
3 (Amazonia; Mittermeier et al., 2003). To protect these natural resources, governments have
4 implemented strict environmental conservation laws since the beginning of the Amazon's
5 colonization period. The first Forest Law was published in 1934 (Drummond and Barros-
6 Platiau, 2006). Its current version claims that land owners are not only forbidden from
7 clearing more than 20% and 65% of their properties in the forest and cerrado ecoregions,
8 respectively, but must also protect the Areas of Permanent Preservation, such as the riparian
9 systems, steep slopes, hill tops and elevated areas (CodigoFlorestal, 1965; Sparovek et al.,
10 2010). However, these limits are currently being revised by the Brazilian government because
11 they are considered to be either extremely conservationist, especially by farmers, or
12 insufficiently enforced, especially by environmentalist NGOs. Despite these restrictive laws,
13 deforestation has already highly impacted the forest and the cerrado ecoregions. Whereas
14 previous scholars have since long proven that the forest area was suffering from high
15 deforestation rates (INPE, 2010a), Ferreira and Huete (2004) as well as Sano et al. (2010)
16 recently estimated that 40% of the cerrado had already been cleared in 2004 and 2002,
17 respectively. Moreover, the same authors argued that between 11% and 13% of the Brazilian
18 cerrado (i.e., approximately 23 million hectares) were covered by natural grasslands used for
19 cattle ranching.

20
21 Figure 1 close to here

22
23 Prior researchers have identified crop expansion as one of the main drivers of deforestation in
24 Mato Grosso (Fearnside, 2002; Cardille and Foley, 2003; Morton et al., 2006). This expansion
25 process was led by farmers who arrived in the '70s, '80s and '90s from Southern Brazil

(Jepson et al., 2006). In 2009, these migrants developed a powerful mechanized agricultural system that cultivated a total planted area of 87354 km², which represents 14.7% of the total planted area in Brazil (IBGE, 2010). In this area, soybeans were planted in 66.7% of the land, corn was planted in 19% and cotton was planted in 4.1%. These crops represent the three main commodities cultivated in Mato Grosso. According to the official agricultural statistics (IBGE, 2010), the land in which all of these crops have been planted has expanded considerably (+275%, +509% and +723% for soybean, corn and cotton, respectively) during the past 20 years. At the same time, yields have also increased (+56%, +117% and +198% for the three respective crops) such that the soybean yields in Mato Grosso (3.08 tons/hectare) were estimated to be 17% higher than the national average (2.63 tons/hectare) in 2009.

2.2. Agricultural practices

In Mato Grosso, the farmers usually planted soybean and cotton crops in single cropping systems. Soybean crops are planted from late September to early November, which corresponds to the onset of the rainy season, and harvested from January to March. The cotton crops are sown in December and harvested in June and July. However, single cropping systems have been called into question because of their harmful environmental and economic impacts. Major problems concerning water pollution and the loss of soil fertility were noticed because the soils remained vulnerable to heavy rainfalls that occurred after the soybean harvest (Bernoux et al., 2006). Moreover, the high level of monoculture rendered the crops highly vulnerable against a new soybean disease, the “Asiatic rust”, which appeared during the 2002-2003 harvest. Finally, the unfavorable exchange rate between the Brazilian currency (real) and the US dollar from 2005-2007 highlighted the economic vulnerability of the region’s producers to soybean monoculture (Arvoret et al., 2009).

To reduce their environmental and economic vulnerability, the soybean producers changed their agricultural management practices. In the 1990s, they started planting a second non-commercial crop (i.e., generally millet or sorghum, which are cheaper than other off-season crops) after the soybean harvest such that the residual vegetation from the second harvest allowed the producers to adopt a no-tillage practice (Landers, 2001). Also called soil and water management by Tappan and McGahuey (2007), this practice is especially useful for improving the soil's quality by limiting the loss of chemical products and organic matter via erosion and by retaining water for a longer period, which allows farmers to achieve better yields (Borlaug, 2000b; Scopelet al., 2005). In the early 2000s, the farmers began cultivating commodities such as corn and cotton in double cropping systems. In this system, the corn and cotton crops are sown from January to February and harvested in June and July. In this way, new management practices improved the diversification process, optimized the use of fertilizers and helped fight against crop diseases (Tilmanet al., 2002).

3. Data and Methods

To study the agricultural transition in Mato Grosso from 2000-2006, we used spatio-temporal data to develop and calculate indices to characterize the region's agricultural dynamics(i.e., agricultural expansion, agricultural intensification and ecological intensification).

3.1. Data

3.1.1. Vegetation map

We used the vegetation map of Mato Grosso provided by the Secretary of Environment of Mato Grosso (SEMA-MT) to conduct the study at the ecoregion level. This map was created

as part of the PRODEAGRO project led by the Brazilian government in the late 1980s. The map classified the region's primary vegetation by using 14 classes. We restructured these classes to consider only the two main ecoregions: cerrado and forest. We did not consider the Pantanal ecoregion because there are no arable lands for mechanized agriculture. We classified the transition class called "contact between cerrado and ombrophilous forest" as the forest because its definition assumed that its physiognomic vegetation properties were closer to the forest than to the cerrado (RADAMBRASIL project, 1982).

3.1.2. Deforestation maps

We computed annual deforestation maps for the 2001-2005 (Fig. 2) period based on two datasets. First, we obtained annual deforestation maps from the INPE through the PRODES digital website (INPE, 2010b) for the period from 2000-2006. The PRODES maps have been annually and semi-automatically produced since 1997 (Shimabukuro et al., 1998; Camara et al., 2006) based on Landsat data. However, these maps do not account for the presence of secondary forest and only consider the deforestation in the forest ecoregion (Carreiras et al., 2006; Hansen et al., 2008). Second, the SEMA-MT attempted to solve this issue by having experts produce maps based on Landsat and CBERS data. We obtained these maps for the entire state of Mato Grosso, including the cerrado for the 1992-2005 time period. Some years (i.e., 1994, 1996, 1998, and 2000) were missing in these maps. By using these maps, we produced integrated annual maps of deforested areas in which a single pixel was considered to be deforested if at least one data source (i.e., PRODES or SEMA) labeled the pixel as deforested in the forest area and if the SEMA's data source labeled it as deforested in the cerrado area.

Figure 2 close to here

3.1.3. *Agricultural maps*

Most studies on crop mapping using MODIS data were based on multi-temporal classifications of spectral vegetation indices (see Jasinski et al., 2005; Morton et al, 2006; Brown et al., 2007; Galford et al., 2008; Redo and Millington, 2011 for applications in Mato Grosso and its surroundings). In the present study, we applied a similar approach by using MODIS/Terra EVI (i.e., the Enhanced Vegetation Index) data at a 250 m spatial resolution and a 16-day temporal resolution (MOD13Q1 product; Huete et al., 2002). The entire methodology is detailed in Arvor et al. (2011) and has been validated based on an extensive field campaign. This methodology consisted of two successive classifications aimed at creating an agricultural mask and at mapping the crop classes. These crop classes consisted of two classes of single cropping practices (i.e., “soybean” and “cotton”) and three classes of double cropping practices (i.e., “soybean + non-commercial crop”, “soybean + corn” and “soybean + cotton”) (see figure 3 for a detailed explanation of the EVI time series corresponding to these classes). Both classifications were based on the following five-step methodology. First, we analyzed the MODIS/ Terra EVI time series corresponding to each land use class observed during the field campaigns. Second, we applied a smoothing algorithm to reduce the noise in the EVI time series (Arvoret al., 2008). Third, we selected/extracted the attributes of the EVI time series to reduce the dimensionality of the input data. Fourth, we applied a maximum likelihood classifier, and finally, we applied a post-classification treatment based on the transition rules and segmentation (Jonathan et al., 2008). Because we detected agricultural areas with user’s and producer’s accuracies (Story and Congalton, 1986) higher than 95%, the quality of the agricultural mask was validated. We

also correctly detected the crop classes with good Kappa index (0.675) and Overall Accuracy (74%), but a few areas of confusion appeared as well, especially with the "soybean + non-commercial crop" class. We preferred to group the coherent classes together to produce high quality maps of the cropping systems. We detected the double cropping systems with two commercial crops (i.e., the "soybean + corn" and "soybean + cotton" classes were grouped together) with user's and producer's accuracies of 95% and 86%, respectively. Additionally, we classified the permanently covered areas (i.e., the "soybean + corn", "soybean + cotton" and "soybean + non-commercial crop" classes were grouped together) with user's and producer's accuracies of 85% and 89%, respectively. In doing so, we provided the annual agricultural maps from the cropping years in 2000-2001 until the cropping years in 2006-2007. In turn, these maps allowed us to estimate the areas cultivated for each crop or cropping system (Table 1). These maps also allowed us to identify the four main agricultural regions (Fig. 4): the Parecis plateau, which is located in the western region of Mato Grosso around the Sapezal municipality; the BR163 region, which is located along the BR163 highway in the central area of Mato Grosso near the Lucas do Rio Verde municipality; the Southeastern region, which is located around the Rondonopolis municipality, and the Eastern region, which is located around the Querência municipality (Fig. 4).

Figure 3 close to here

Table 1 close to here

Figure 4 close to here

3.2. Method

Based on the agricultural maps (see section 3.1.3), we analyzed the agricultural transition in Mato Grosso by defining a list of indices that provided information on the three stages of the agricultural transition process: agricultural expansion, agricultural intensification and ecological intensification (Table 2). To further our understanding of these indices, we must define the following four terms:

- **NC** refers to the **Net Cropped** area (i.e., the agricultural area) independently from the cropping system applied to the area (i.e., the NC gives equal consideration to all of the cropped areas being cultivated with single or double cropping systems).
- **DC** refers to the agricultural area cultivated with **double cropping systems involving two commercial crops** (i.e., soybean, corn or cotton).
- **TC** refers to the **Total Cropped** area calculated by adding NC and DC. Unlike the Net Cropped area, this index is linearly linked to the agricultural production.
- **PC** refers to the agricultural area that is permanently **covered by crop vegetation during the rainy season** (i.e., from September to May). PC corresponds to the areas cultivated with double cropping systems that involve either two commercial crops or one commercial crop (i.e., soybean) followed by one non-commercial crop (i.e., millet or sorghum).

These terms (NC, DC, TC and PC) reflect the main agricultural land use types observed in Mato Grosso and are illustrated in Fig. 5 based on a basic example.

Figure 5 close to here

Table 2 close to here

3.2.1. *Agricultural expansion indices*

Agricultural expansion consists of converting land into cropland and is described by the evolution of the three indices (Table 2). We calculate the annual NC (Net Cropped) index by using the agricultural maps derived from the MODIS Terra/EVI time series. We use the index to quantify the evolution of the Net Cropped area from 2000-2006 for each ecoregion (i.e., forest and cerrado) in the entire state of Mato Grosso.

The next two indices, DEF and EXP, describe the direct expansion of agricultural land in relation to the deforestation process. Direct agricultural expansion refers to the process of converting previously unused areas of natural vegetation into new production areas. Redo and Millington define this process as extensification (2011). In Mato Grosso, producers are used to waiting for one or two years after clearing an area before planting soybeans in the area for the first time (Rudorff et al., 2011). These producers consider using direct conversions if they detect crop areas within two years after a region is deforested. Two indexes are useful in this regard. First, the DEF index represents the proportion of deforested land in which a crop has been detected at least once during the two years following the clearing of the land. Second, the EXP index represents the proportion of agricultural expansion that was observed for recently cleared areas (i.e., up to two years before the first crop was detected).

3.2.2. *Agricultural intensification indices*

Agricultural intensification occurs if an area experiences higher levels of both inputs and outputs (in quantity or value) of cultivated or reared products per unit area and time (Lambinet al., 2001). Thus, we assumed that double cropping systems involving commercial crops (i.e., soybean, corn and cotton) constitute a type of agricultural intensification because these systems increase both inputs and outputs in one area. We did not consider double cropping systems involving non-commercial crops (i.e., millet or sorghum after a soybean

harvest) because farmers adopt these systems not to increase their outputs but to protect the soil from erosion, improve the soil's quality, break the pest cycles, maintain the soil's moisture and set the conditions for high-quality no-tillage operations (Landers, 2001). Following this assertion, we calculated three indices based on the agricultural maps issued from the MODIS EVI time series to identify the importance of the agricultural intensification process (Table 1).

We used the DC (Double Cropping) index to quantify the evolution of the double cropping area for each ecoregion (i.e., forest and cerrado) in the entire state of Mato Grosso from 2000-2006.

We calculate the DC/NC (Double Cropping area/Net Cropped area) index to measure the evolution of the annual proportion of the net cropped area sown with double cropping systems involving two commercial crops. This index is an indicator of the arable lands' intensification levels.

We use the DC/TC (Double Cropping area / Total Cropped area) index to estimate the evolution of the proportion of the total cropped area sown with double cropping systems involving two commercial crops. This index is an indicator of the proportion of the agricultural production caused by agricultural intensification.

3.2.3. Ecological intensification indices

The principles of ecological intensification are based on the adoption of new agricultural management practices designed to improve fertilizer efficiency, improve water use efficiency, maintain and retrieve soil fertility, and improve the monitoring of crop diseases (Tilman et al., 2002). We defined two indices to analyze the ecological intensification process (Table 2). First, the PC index (i.e., the area permanently covered by crop vegetation during the rainy season) represents the proportion of the net cropped area that is permanently covered by a

crop during the entire rainy season for each cropping year. In this study, we consider the areas cultivated with double cropping systems that involve both commercial (i.e., corn, soybean, cotton) and non-commercial crops (i.e., millet and sorghum) to be permanently covered by crops. We consider this index to be a sign of ecological intensification because it allows farmers to improve soil quality, break pest cycles, maintain soil moisture, and set the conditions for high-quality no-tillage operations for the following soybean crop. The Area Diversity Index (ADI) proposed by Ray et al. (2005) allows us to measure the level of crop diversification based on Equation 1 as follows:

$$ADI = \frac{1}{\sum_{i=1}^n \left(a_i / \sum_{i=1}^n a_i \right)^2} \quad (\text{eq. 1})$$

where a_i is the area sown with the i^{th} crop. The maximal value of ADI is the number of crops that are considered. In this study, we consider four crops, which correspond to the number of crop classes mapped in the classification process (described in section 3.1.3.). These crop classes are soybean, corn, cotton and the non-commercial crops. Note that non-commercial crops refer to millet and sorghum, which were grouped together because the classification tests indicated that these crops could not be accurately distinguished from each other. Thus, in this study, $ADI = 4$ indicates that cultivated areas for soybean, corn, cotton and non-commercial crops are equal. In contrast, $ADI = 1$ indicates that a monoculture situation exists. We consider diversifying because doing so allows farmers to optimize their use of fertilizers while improving their abilities to monitor for crop diseases (Kennedy et al., 2002; Tilman et al., 2002).

4. Results and discussion

4.1. Agricultural expansion

1
2 In Mato Grosso, the net cropped area (NC) expanded by 43% during the course of the study
3 period (Fig. 6) and reached a value of 55988 km² in the 2006-2007 cropping year. We found
4 that the net cropped area obtained its peak (61140 km²) one year earlier during the 2005-2006
5 harvest. The subsequent decrease was due to the economic crisis, where the Brazilian
6 currency was devalued compared with the US dollar, that affected the producers from 2005 to
7 2007 (Arvoret al., 2009). Although the net cropped areas of both ecoregions rapidly increased
8 at the state level, the areas expanded at different rates for each ecosystem. The rate of
9 agricultural expansion was more pronounced in the forest ecoregion than in the cerrado
10 ecoregion. Fig. 7 shows that 24% of the forest ecoregion consisted of NC in 2000-2001,
11 whereas 36% of the region consisted of NC in 2006-2007. Similarly, Fig. 4 shows that the
12 major agricultural expansion occurred in the Central and Eastern agricultural regions (i.e.,
13 regions B and D, respectively, in Fig. 4), both of which are mainly located in the Amazonian
14 forest.

15 The DEF index indicates that 12.6% of the deforested area in Mato Grosso was directly
16 converted into cropland from 2001 to 2004 (i.e., within two years after deforestation). This
17 result implies that other important drivers of deforestation, such as cattle ranching or timber,
18 may have had a more important impact on deforestation in Mato Grosso than crop expansion.
19 However, the DEF index calculated at the Mato Grosso scale corresponds to an area of
20 7771 km², of which 4950 km² consisted of forest land. Thus, the direct impact of mechanized
21 agriculture on deforestation cannot be understated. In addition, the EXP index indicates that
22 27% of the crop expansion that occurred during the cropping years from 2002-2003 to 2005-
23 2006 was based on direct conversions of native vegetation areas into cropland. Although this
24 rate may also appear to be low, it represents 4796 km² at the state level.

Both indices indicate that the direct link between agricultural expansion and deforestation is stronger in the forest ecoregion (DEF = 15.7%; EXP = 33%) than in the cerrado ecoregion (DEF = 8.7%; EXP = 19%). Because the agricultural expansion in the forest ecoregion primarily occurred at the BR163 region (i.e., region B on figure 4), we can conclude that the most direct conversions from forest land to crop land occurred in this area. Two main reasons may explain why farmers are attracted to this region. First, the BR163 region has the highest soybean yields in Mato Grosso. The mean soybean yields in Lucas do Rio Verde from 2000 to 2009 is 3.14 tons/ha, whereas the state's average is 2.96 tons/ha (IBGE, 2010). Thus, farmers have more resources and reasons to invest in this region. Second, the government plans to asphalt the BR163 highway until it connects with the Santarem harbor in the state of Para on the Amazon river, regardless of the potential environmental consequences (Fearnside, 2007). This plan created new expectations that soybean production costs would decrease in this region (Fearnside, 2007).

Figure 6 close to here

Figure 7 close to here

4.2. Agricultural intensification

While the net cropped area expanded in Mato Grosso, farmers adopted new agricultural management practices (e.g., double cropping systems) to intensify the production process. During the study period, the area cultivated with double cropping systems involving two commercial crops (DC index) increased constantly and drastically (+590%) from 2442 km² during the 2000-2001 cropping year to 16773 km² during the 2006-2007 cropping year (Fig.

6). As a result, the proportion of the net cropped area sown with two successive commercial crops (DC/NC index) increased from 6% in 2000-2001 to 30% in 2006-2007 (Fig. 8). We found the same conclusion when we observed the annual proportion of the total cropped area cultivated with double cropping systems utilizing two commercial crops (DC/TC index) (Fig. 8). This area increased from 5.8% to 23%, which indicated that nearly one-quarter of Mato Grosso's agricultural production was based on intensive agriculture. Both indices showed similar increasing patterns, with a common spike in intensive agriculture during the 2006-2007 cropping year. This spike is explained by the decrease in NC combined with an increase in DC during this year. One can conclude that, although the net cropped area decreased, the farmers partly compensated for the loss in production by adopting the double cropping systems. As a result, the total cropped area ($TC = NC + DC$) remained nearly constant during the last two cropping years of the study period (Fig. 6).

Our results indicated that from 2000 to 2006, the total cropped area in Mato Grosso increased faster (i.e., +75%; from 41616 km² to 73023 km²) than the net cropped area (i.e., +43%; from 39180 km² to 56172 km²) because the farmers implemented many double cropping systems with two commercial crops. We estimated that during these seven cropping years, 46% of the increase in the total cropped area was due to the adoption of intensive agricultural management practices. Although agricultural expansion remained the main method that producers used to increase their production during the study period, this process clearly evolved throughout the period.

The maps of agricultural intensification (Fig. 9) indicate that agricultural intensification experiences a strong level of spatial variability at the regional level. For all of the agricultural intensification indices (DC, DC/NC and DC/TC), the results were higher in the cerrado ecoregion than in the forest ecoregion. For instance, in the Lucas do Rio Verde municipality (located in the cerrado ecoregion; region B in Fig. 4), the proportion of the cultivated area

with double cropping systems increased from 50% to 90% during the study period. However, the proportion of the area with double cropping systems did not surpass 1% in the Querência municipality (located in the forest ecoregion; region D in Fig. 4) during the 2006-2007 cropping year.

Figure 8 close to here

Figure 9 close to here

4.3. Ecological intensification

In Mato Grosso, the proportion of the net cropped areas permanently covered by vegetation (PC/NC) increased drastically from 35% in 2000-2001 (13741km²) to 62% in 2006-2007 (34543km²) during the study period (Fig. 8). This practice allowed the producers to not only improve the quality of the soil and the efficiency of their water use but also enabled them to adopt no-tillage practices during the following soybean harvest to improve their yields. The 2006-2007 cropping year is quite interesting because of the various reasons explaining the increases in both the PC/NC and the DC/NC indices. When the common denominator NC decreased, the numerator PC remained constant while DC increased. We can explain this difference between the evolution of the PC and DC indices by noting that, when soybean prices were low, the producers decided to pay more attention to other commercial crops to compensate for the low benefits of the soybean harvest. Thus, the producers invested more in corn and cotton after the soybean harvest instead of sowing non-commercial crops. For the producers, implementing double cropping systems with commercial and non-commercial crops represented the best method for diversifying agricultural production. The

1 evolution of the Area Diversity Index, which increased from 2 to 2.51 during the study period,
2 confirms this notion (Fig. 10). This evolution is mainly explained by the large increases in the
3 areas sown with corn (+554%; from 2331 km² to 15244km²), cotton (+40%; from 4041 km² to
4 5655km²) and non-commercial crops (+57%; from 11299 km² to 17770 km²). Fig. 10 also
5 indicates that the ADI is much higher in the cerrado ecoregion than in the forest ecoregion.

6
7 Figure 10 close to here

8 9 **5. General discussion**

10
11 Scholars have highly criticized agricultural development in the state of Mato Grosso because
12 of the environmental impacts (i.e., deforestation and pollution) and the economic vulnerability
13 of this process (Fearnside, 2002). Although the results introduced in this study provide
14 relevant answers to the three objectives of this paper (i.e., analyze the agricultural
15 intensification process, the ecological intensification process, and the impact of agricultural
16 expansion on deforestation), the complexity of the agricultural transition process needs to be
17 further discussed.

18 19 ***5.1. Agricultural expansion and deforestation: issues linked to data quality and the applied*** 20 ***methodology***

21
22 All of the results presented in this paper are highly dependent on the input data. One must be
23 aware of the various constraints linked to each one of the datasets introduced in this study
24 (section 3.1). For instance, although we quantified the accuracy of the classification
25 methodology used to generate the agricultural maps, some confusion remains regarding the

differences between the various classes (e.g., “soybean + corn” and “soybean+non-commercial crop”). This confusion may affect the results of this study. Additionally, we computed the deforestation maps by employing two different datasets to better cover the deforestation in Mato Grosso. However, our methodology implies that our analysis is based on the maximum extent of deforestation. As a result, our findings on the relationship between deforestation and agricultural expansion (i.e., DEF and EXP indices) may be slightly underestimated. Finally, we used the vegetation map from the PRODEAGRO because it was considered to be the most accurate vegetation map available. However, there are other ecoregion maps, such as the one provided by the IBGE (http://www.ibge.gov.br/english/geociencias/cartografia/default_geog_int.shtm). These maps may lead to slightly different results. Specifically, the IBGE’s map may be particularly relevant because of its legal implications. The Forest Law is different for the cerrado and forest areas, and the official distinction between the ecoregions is based on the vegetation map from the IBGE.

From a methodological point of view, our analysis focused on the direct impact of agricultural expansion on deforestation. Our results corroborated the farmers’ arguments that soybean expansion is not the main cause of deforestation in Amazonia because this expansion is mainly conducted within formerly deforested areas. This expansion process has also been encouraged by the Soy Moratorium established by the producers, NGOs, state administrations and private enterprises in 2006 (Rudorff et al., 2011). Although this Moratorium was designed to limit direct conversions of forest land to soybean cropland by prohibiting the sales of soybeans produced on areas deforested after 24th July 2006, we found that the amount of land deforested for the sake of soybean production remains high (i.e., 7771 km² from 2001 to 2004, of which 4950 km² were in the forest ecoregion). Thus, the impact of soybean expansion on deforestation must not be minimized. However, one must also consider the

indirect impact of soybean expansion on deforestation. Arima et al. (2011) proved that the conversions of formerly deforested areas, such as pastures, into soybean areas in settled agricultural areas are statistically linked with forest loss in the frontiers of the Amazon basin. Hence, the indirect land use changes (ILUC) due to soybean expansion call into question the efficiency of the Soy Moratorium (Arima et al., 2011). Lapola et al. (2010) go further by suggesting that the ILUC resulting from the combined expansion of soybean and sugar cane areas for biofuel production may offset the carbon savings achieved from producing biofuels.

5.2. Agricultural intensification: a driver of deforestation?

Because deforestation in tropical areas is a major issue for the global environment, agricultural intensification has long been expected to be a solution to reducing the role of agriculture as a driver of deforestation. Norman Borlaug has championed this hypothesis (Borlaug, 2000a) since the 1960s by arguing that the Green Revolution was the best method for limiting deforestation. However, this hypothesis depends on the scale of the deforestation process. Walker (2012) explained that, at the Brazilian scale, the expansion of agriculture in the Amazon basin and the resulting deforestation may actually be linked to a loss of agricultural land in the Atlantic forest, where scholars have found that both an agricultural intensification process and a Forest Transition process (i.e., a spatial recovery of forest ecosystems after prolonged periods of agricultural land use) is occurring.

At the Mato Grosso scale, we estimated that without agricultural intensification (i.e., without adopting double cropping systems with two commercial crops), farmers would have to cultivate an additional 16800 km² to achieve agricultural production equivalent to the production achieved in 2006-2007. Thus, agricultural intensification may be considered an efficient method for limiting deforestation and for helping the Brazilian government achieve

its objective of reducing deforestation to 20% of the historical (1996-2020) rate by 2020 (Nepstad et al., 2009). Recent annual deforestation estimates produced by the INPE confirm this hypothesis because deforestation has decreased from 11 814 km² in 2004 to 1049 km² in 2009 (INPE, 2010a). However, at the local scale, Borlaug's hypothesis is affected by the individual economic goals of the farmers. As a result, the relation between agricultural intensification and deforestation remains a complex matter at the regional scale. Angelsen and Kaimowitz (2001a, 2001b) provided a contradictory hypothesis on this topic. According to these authors, agricultural intensification may limit deforestation because the ensuing economic development will attract new non-agricultural activities and people with new environmental demands. However, agricultural intensification may also encourage deforestation because of the high benefits this process generates. Specifically, agricultural intensification attracts new migrants and provides producers the financial conditions needed to clear new areas. Hence, additional studies are needed to check if the "win-win" relation observed at the global scale (i.e., more food production and less deforestation) is transformed into a "win-lose" relation at the regional scale (i.e., more crop production but more deforestation).

5.3. Ecological intensification: methodological issues related to the definitions of the relevant indices

We consider diversification and permanent soil cover to be two signs of ecological intensification because these factors enable farmers to better defend their crops against diseases and reduce soil erosion. These indices may indicate that agriculture in Mato Grosso is entering the second phase of the Environmental Kuznets Curve (EKC), where the sector experiences increased economic development and decreased environmental degradation.

1 However, Chowdhury and Moran (2012) warn that the complexity and the multiple
2 dimensions of environmental problems increase the difficulty of choosing the correct
3 indicator of degradation. Depending on the planted crops, the ecological practices chosen as
4 the basis of the ecological indices (i.e., diversification and permanent soil cover) may be
5 subject to criticism. For example, planting cotton crops require large quantities of agrotoxic
6 chemicals. More than fifteen applications are required per cotton harvest, whereas only 6 or 7
7 applications are required for each harvest of soybean. Thus, the expansion of cotton crops
8 may have important impacts on a region's water and soil quality. This effect may be
9 exacerbated if the cotton crops are sown after a soybean harvest. This problem is particularly
10 relevant to the Xingu river basin because all of the main headwaters are located outside of the
11 protected Xingu land in the region's soybean and cotton production areas, whose resulting
12 pollution may affect the indigenous communities living inside the land (Brondizio et al.,
13 2009).

15 **5.4. Agricultural transition and globalization**

17 The results indicate that the agricultural sector in Mato Grosso is witnessing rapid changes.
18 Keys and McConnell (2005) showed that various factors, such as biophysical factors,
19 demographic factors, market influences and institutional factors, may explain these changes.
20 In Mato Grosso, one must consider the market influences while paying particular attention to
21 the agricultural dynamics of the market. After the soybean crisis from 2005 to 2007, Mato
22 Grosso's producers were encouraged to adopt agricultural and ecological intensification
23 processes to reduce their economic vulnerability. Thus, the economic crisis seemed to
24 accelerate the agricultural transition process. However, one may wonder whether this
25 tendency will continue if the soybean prices return to being profitable. Morton et al. (2006)

1 proved that a statistical relationship between the expansion of soybean croplands and soybean
2 prices exists ($R^2=0.72$). Recent estimates of soybean areas in Mato Grosso indicate that this
3 question is relevant because after two successive decreases in the size of soybean croplands
4 (i.e., a cumulative reduction of 10466 km² of the soybean croplands from 2006-2008), the
5 official statistics of the 2008-2009 harvest showed an increase of 3951km².

6 7 **6. Conclusion**

8
9 The agricultural transition in Amazonia is linked to important social, economic and
10 environmental issues at the local, regional and global scales. In this paper, we argued that
11 satellite-based indices can help scholars understand the agricultural transition because of the
12 severe land use changes induced. In the state of Mato Grosso (i.e., the area most affected by
13 mechanized agriculture in the Brazilian Amazon), we showed that agricultural expansion
14 remains an important method for increasing agricultural production. The net cropped area
15 expanded by 43% during the study period and reached a total of 55988km². We confirmed the
16 impact of this expansion on the deforestation of the region, as 7771 km² of forest was directly
17 converted into crop land from 2001 to 2004. The results indicate that agricultural
18 intensification based on two commercial crops has become widely accepted by producers. We
19 estimated that farmers cultivated nearly one-quarter of the land available for agricultural
20 production (i.e., 23% of the total cropped area) in Mato Grosso by employing intensive
21 agricultural practices during the 2006-2007 cropping year. This intensification process not
22 only serves to increase the production but also serves as the basis for adopting ecological
23 intensification practices. Producers now adopt double cropping systems that include non-
24 commercial crops to maintain the ecosystems' support and regulatory services by reducing
25 erosion and diversifying their crops.

1 However, important issues remain regarding the evolution of the agricultural transition
2 process in Amazonia. Future researchers can rely on the results described in this paper to
3 study these issues. Scholars must understand the driving forces of the evolution of agricultural
4 systems in Mato Grosso. Prior researchers have already proven that agricultural expansion on
5 a pioneer frontier, such as Mato Grosso, is correlated to commodity prices (Morton et al.,
6 2006). Other researchers should check whether the same prices also impact agricultural
7 practices. For example, the low soybean prices encountered during the soybean crisis that
8 occurred from 2005 to 2007 may have encouraged Brazilian producers to adopt more
9 intensive and ecological management practices. Additionally, future scholars may analyze the
10 relation between agricultural intensification and deforestation. The main remaining questions
11 are related to these processes at the regional scale. Finally, the new agricultural policies
12 applied in Mato Grosso, such as the Soy Moratorium, need to be monitored to validate their
13 efficiency.

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List of tables:

Table 1: Estimated areas (in km²) of the main crops and cropping systems observed in each ecoregion of Mato Grosso and in the entire state (906000 km²). The areas are classified according to the first and last years of the study period (see section 3.2. for the definitions of Net Cropped, Double Cropped, Permanently Covered and Total Cropped areas).

Table 2: List of indices used to characterize the agricultural transition that occurred from the cropping years in 2000-2007.

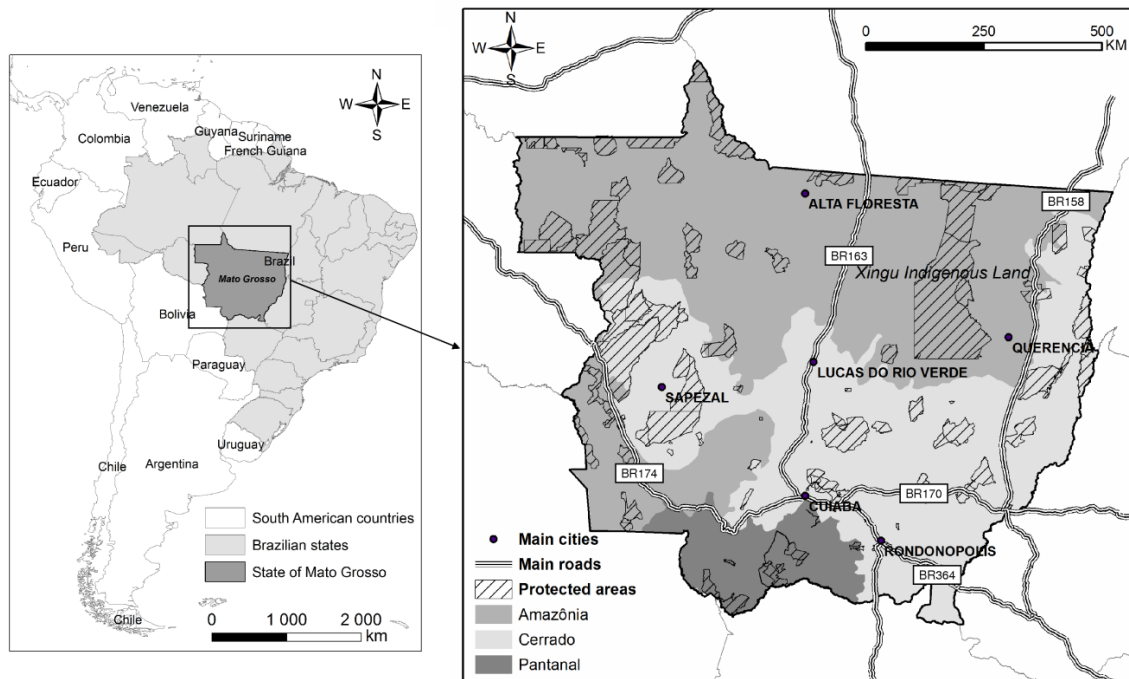
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Cropping system	2000-2001			2006-2007		
	Cerrado	Forest	Mato Grosso	Cerrado	Forest	Mato Grosso
Soybean	26498	8820	35318	32266	19596	51861
Corn	1900	432	2331	10167	5077	15244
Cotton	3539	502	4041	4816	839	5655
Non-commercial crops (millet or sorghum)	8406	2893	11299	10428	7342	17770
Net Cropped area	29944	9305	39248	35847	20141	55988
Double Cropped area	1993	449	2442	11402	5371	16773
Permanently Covered area	10398	3343	13741	21830	12713	34543
Total Cropped area	31936	9754	41690	47249	25512	72761

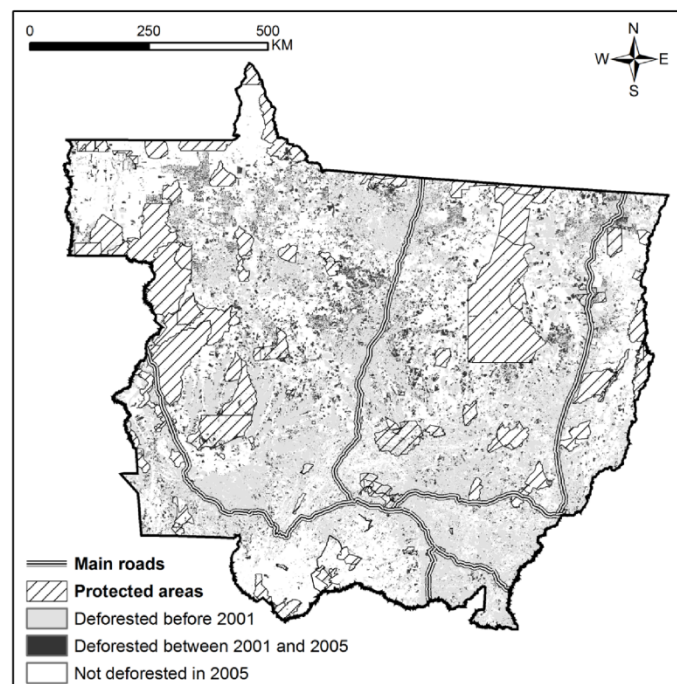
Table 2: List of indices used to characterize the agricultural transition from the cropping years in 2000-2007.

Agricultural model	Index code	Index definition	Unit
Agricultural expansion	NC	Annual net cropped area	km ²
	DEF	Proportion of deforestation that occurred from 2001 to 2004 because the forest land was directly converted into crop lands	%
	EXP	Proportion of agricultural expansion from 2002-2003 and from 2005-2006 because of direct conversions of native vegetation into crop lands	%
Agricultural intensification	DC	Annual area cultivated with double cropping systems utilizing two commercial crops from the cropping years in 2000-2007	km ²
	DC/NC	Annual proportion of the net cropped area cultivated with double cropping systems involving two commercial crops	%
	DC/TC	Annual proportion of the total cropped area cultivated with double cropping systems involving two commercial crops	%
Ecological intensification	PC/NC	Annual proportion of the net cropped area permanently covered by vegetation during the rainy season	%
	ADI	Annual measure of the Area Diversity Index (eq. 1)	Unitless

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2 **List of figures:**



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4 **Figure 1: Location and map of Mato Grosso, with the main ecoregions, roads and protected**
5 **areas.**



6
7 **Figure 2: Deforestation map of Mato Grosso.**

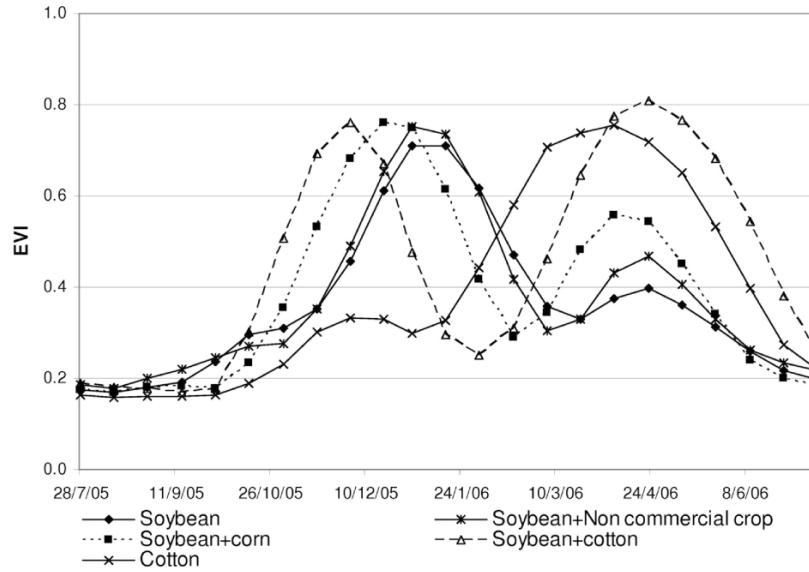


Figure 3: Mean MODIS EVI time series of the five crop classes, which were calculated based on the ground data for the 2005-2006 harvest (Arvor et al., 2011). From the end of July to late September, the EVI values remain low during the dry season. After the onset of the rainy season (October), the farmers plant soybeans. The soybean phenological cycle is the same (i.e., same maximum values and same duration) for the four classes that involve soybean. However, there are temporal differences based on the fact that the soybean planting dates are determined according to the following crop. After the soybeans, the farmers plant cotton because the cotton cycle is longer than the corn cycle. Then the farmers plant soybeans followed by corn, soybeans followed by a non-commercial crop and finally, soybeans planted as a single crop. Even when no crop is planted after soybeans, a small EVI peak appears because of the growth of self-propagating plants and the remaining soybean seeds. The class "soybean + cotton" is characterized by a different EVI time series. The EVI values remain low until January. Then the cotton phenological cycle is characterized by high EVI values and a long cycle (i.e., six months), which is longer than the cotton cycle planted after the soybeans (i.e., five months).

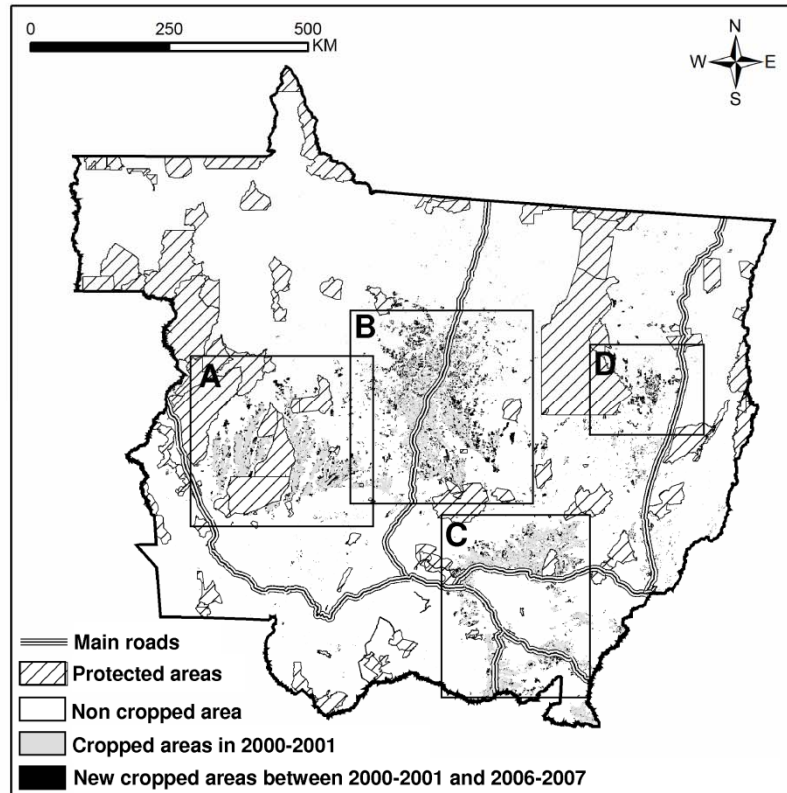


Figure 4: Agricultural expansion in Mato Grosso. The four main agricultural regions are the following: (A) the Parecis plateau, (B) the BR163 region, (C) the Southeastern region and (D) the Eastern region.

Field 1 (Area = 100 ha)	Field 2 (Area = 100 ha)	Field 3 (Area = 100 ha)
Single cropping system One harvest of commercial crop per year <i>Ex:</i> - soybean - corn	Double cropping system Two harvests of commercial crops per year <i>Ex:</i> - soybean + corn - soybean + cotton	Permanently Covered system Two crops (commercial and non-commercial) per year <i>Ex:</i> - Soybean + sorghum - Soybean + millet
NC= 100 ha DC = 0 ha TC = 100 ha PC = 0 ha	NC= 100 ha DC = 100 ha TC = 200 ha PC = 100 ha	NC= 100 ha DC = 0 ha TC = 100 ha PC = 100 ha
NC = 300 ha; DC = 100 ha; TC = 400 ha; PC = 200 ha		

Figure 5: Illustration of our calculations of the Net Cropped (NC) area, Double Cropped (DC) area, Total Cropped (TC) area, and Permanently Covered (PC) area for three fields, each of which contains 100 ha cultivated with different cropping systems.

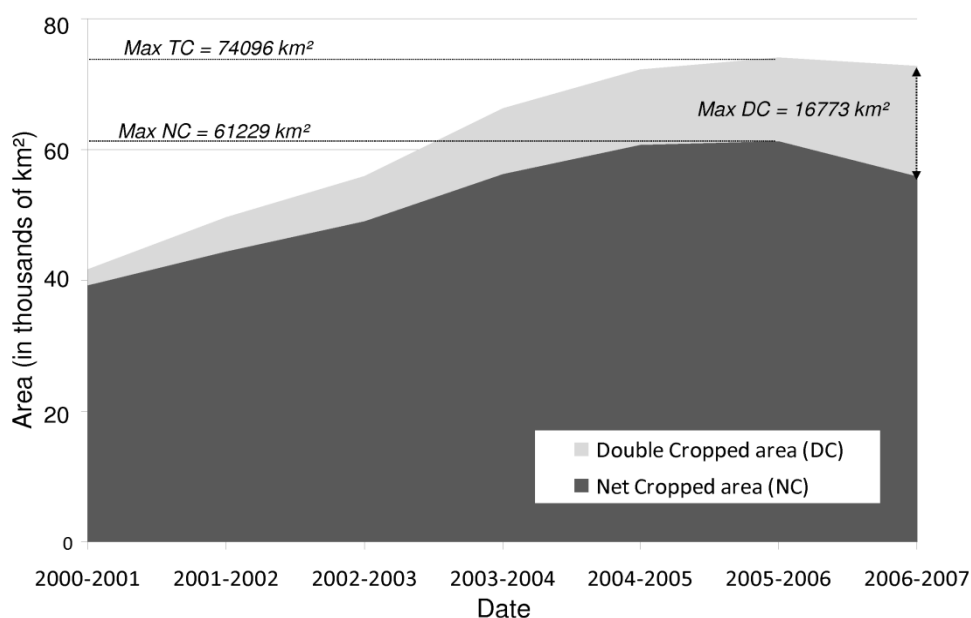
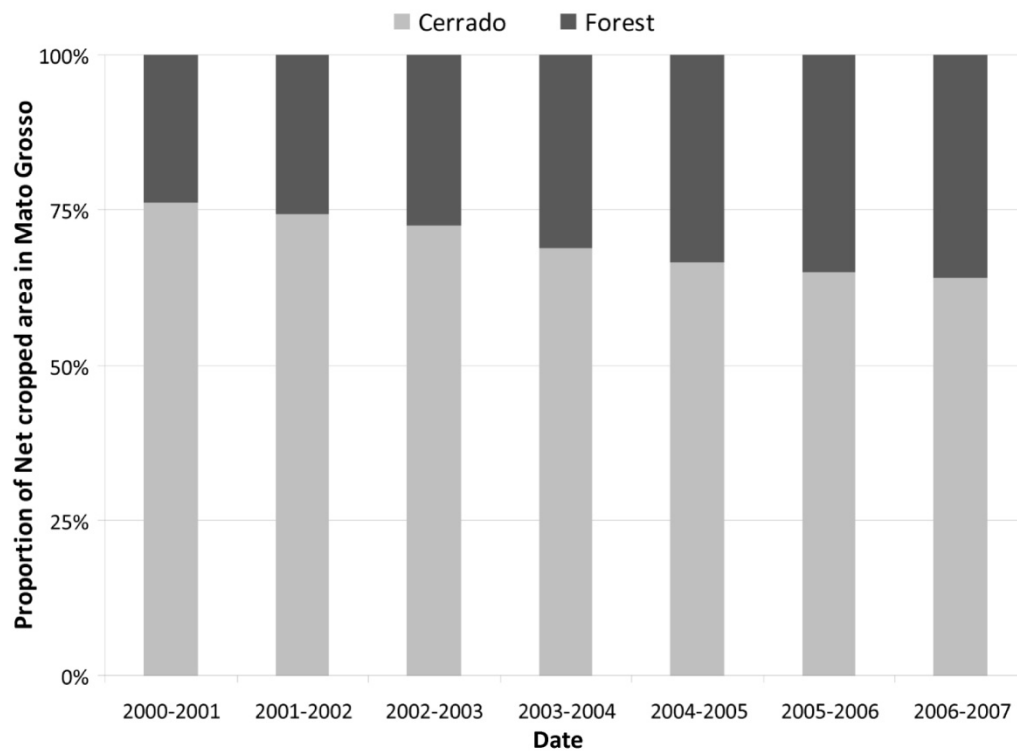


Figure 6: Annual evolution of the Net Cropped (NC) and the Double Cropped (DC) areas in Mato Grosso from the cropping years in 2000-2007. Total Cropped area (TC) corresponds to NC+DC.



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2 Figure 7: Evolution of the relative proportion of agricultural expansion in the ecoregions (i.e.,
 3 cerrado and forest) of Mato Grosso from the cropping years in 2000-2007.

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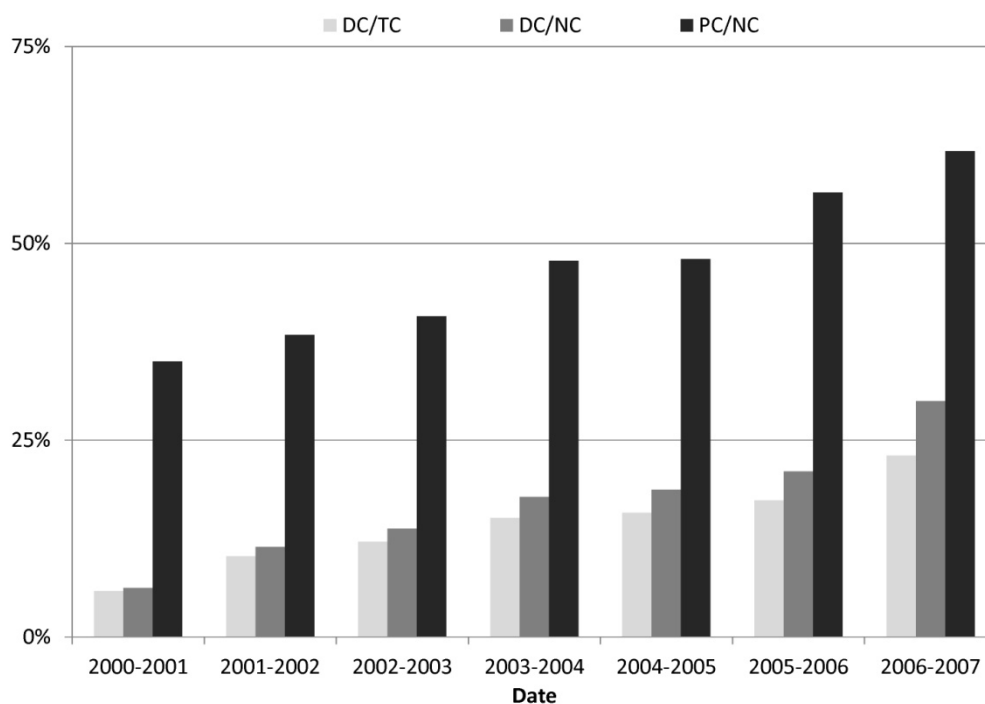


Figure 8: Annual evolution of the proportion of the total cropped area cultivated with double cropping systems using two commercial crops (DC/TC), the proportion of the net cropped area cultivated with double cropping systems using two commercial crops (DC/NC), and the proportion of the net cropped area permanently covered by vegetation (PC/NC) indices in Mato Grosso from the cropping years in 2000-2007.

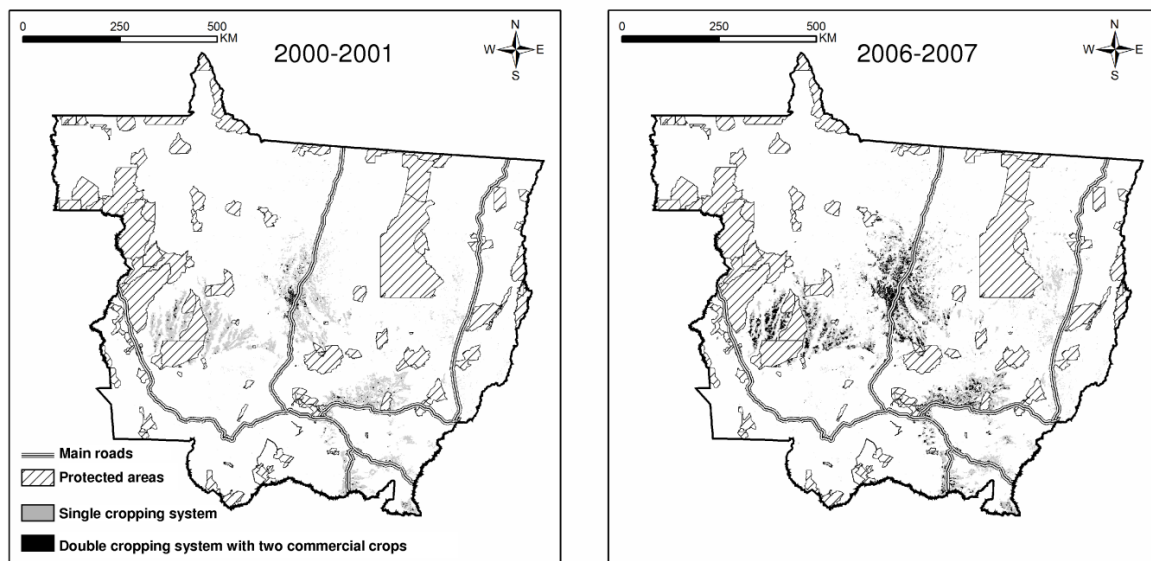


Figure 9: Agricultural intensification in the state of Mato Grosso in 2000-2001 and 2006-2007 cropping years.

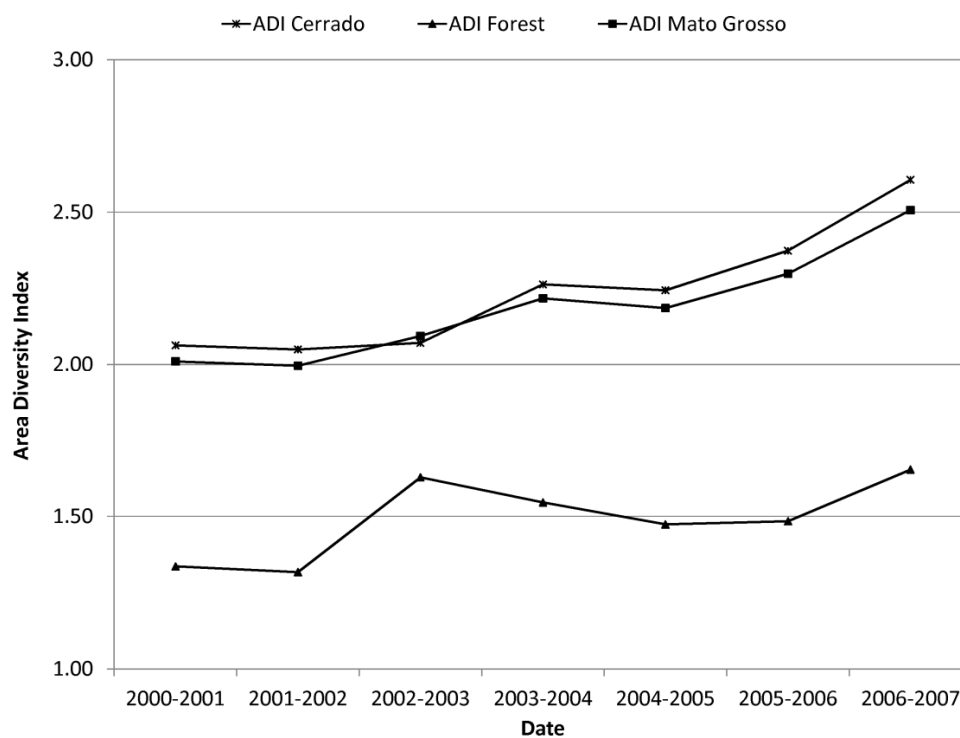


Figure 10: Evolution of the Area Diversity Index between the 2000-2001 and 2006-2007 cropping years.